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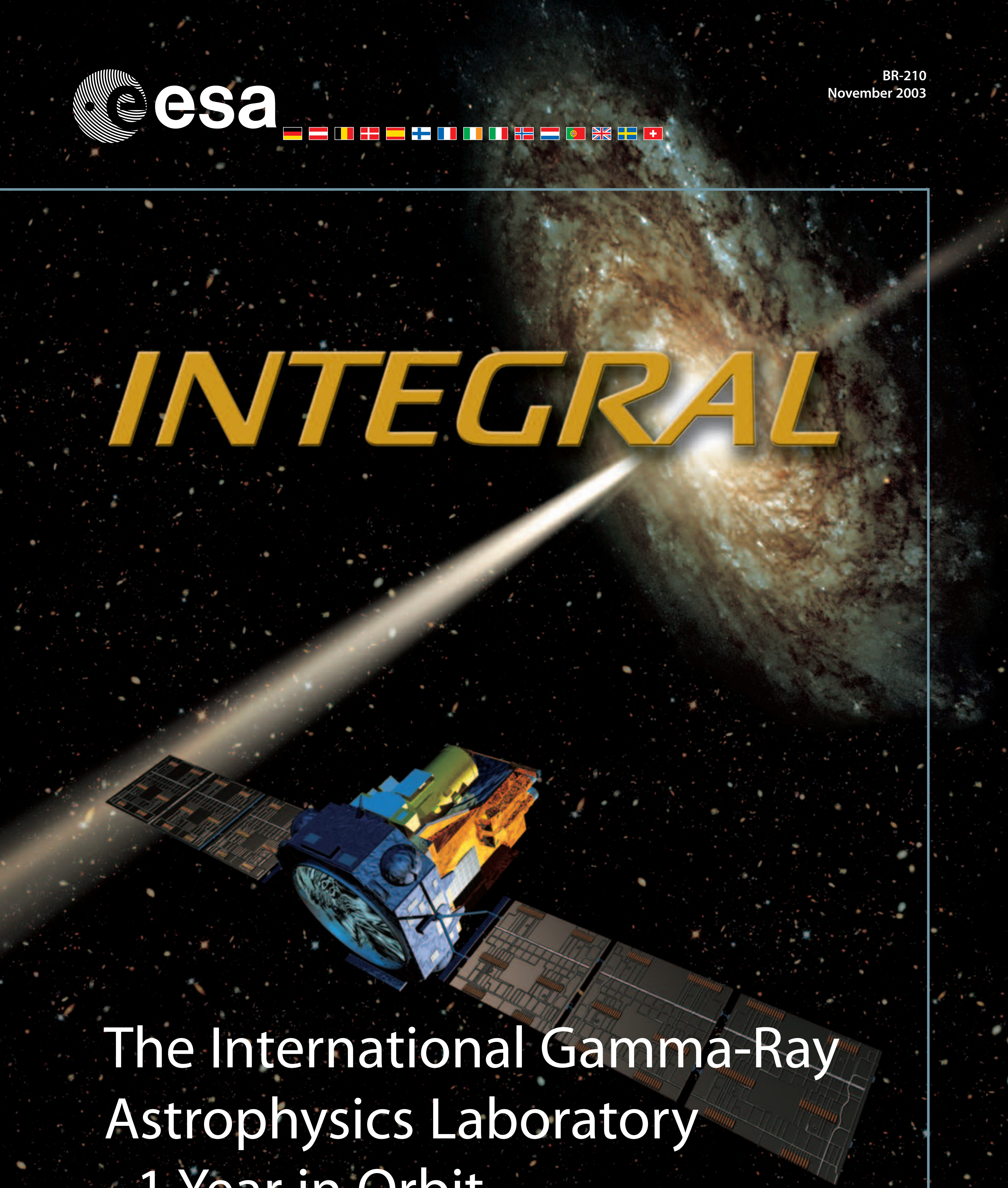
INTEGRAL



The International Gamma-Ray Astrophysics Laboratory - 1 Year in Orbit

European Space Agency
Agence spatiale européenne

Contributors:
Kai Clausen
Phlippe Sivac
Eliseo Balaguer
Giuseppe Sarri
Arvind Parmar
Michael Schmidt
Lars Hansson
Rudolf Much
Paolo Strada

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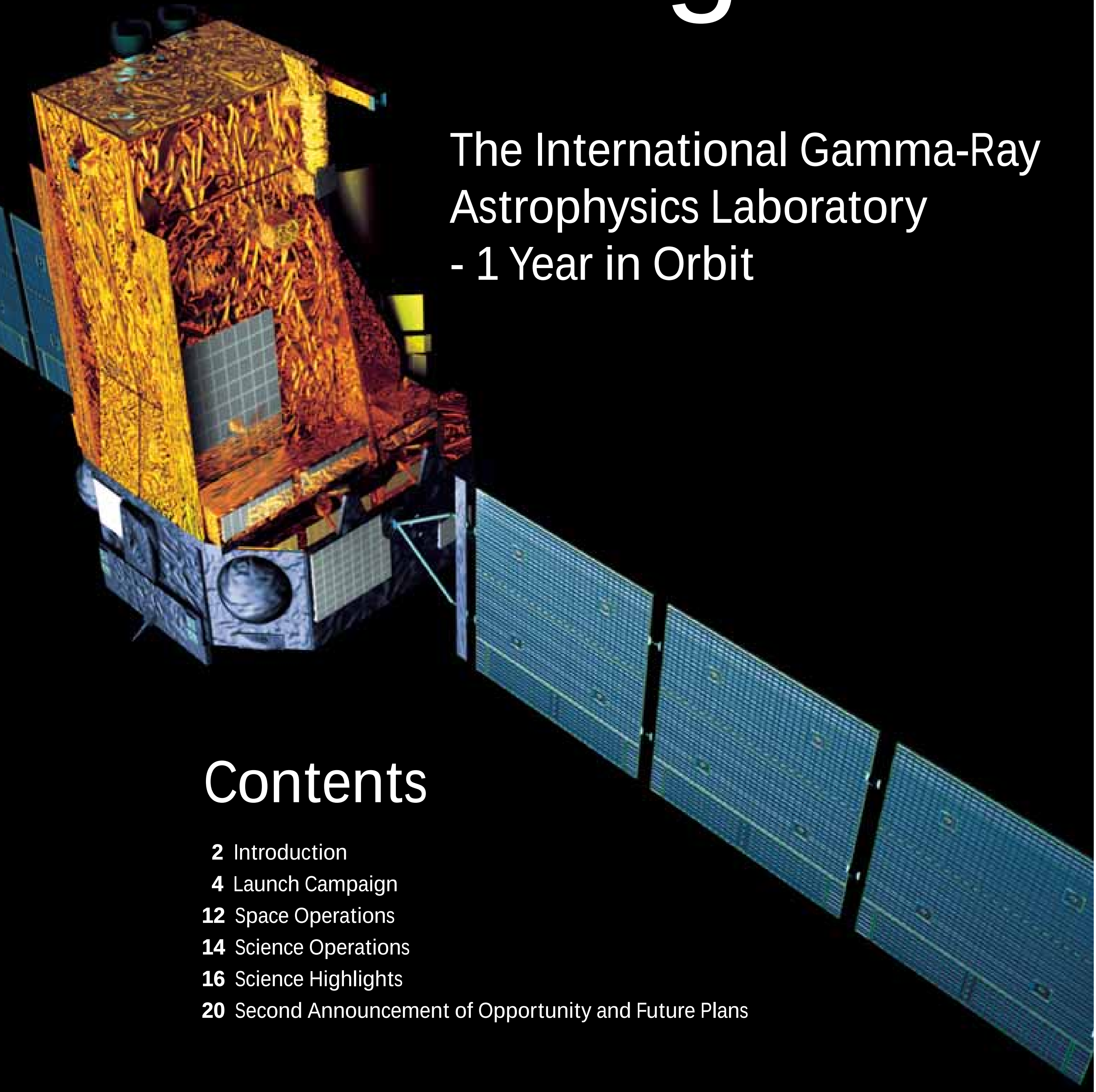
Integral



The International Gamma-Ray Astrophysics Laboratory - 1 Year in Orbit

Contents

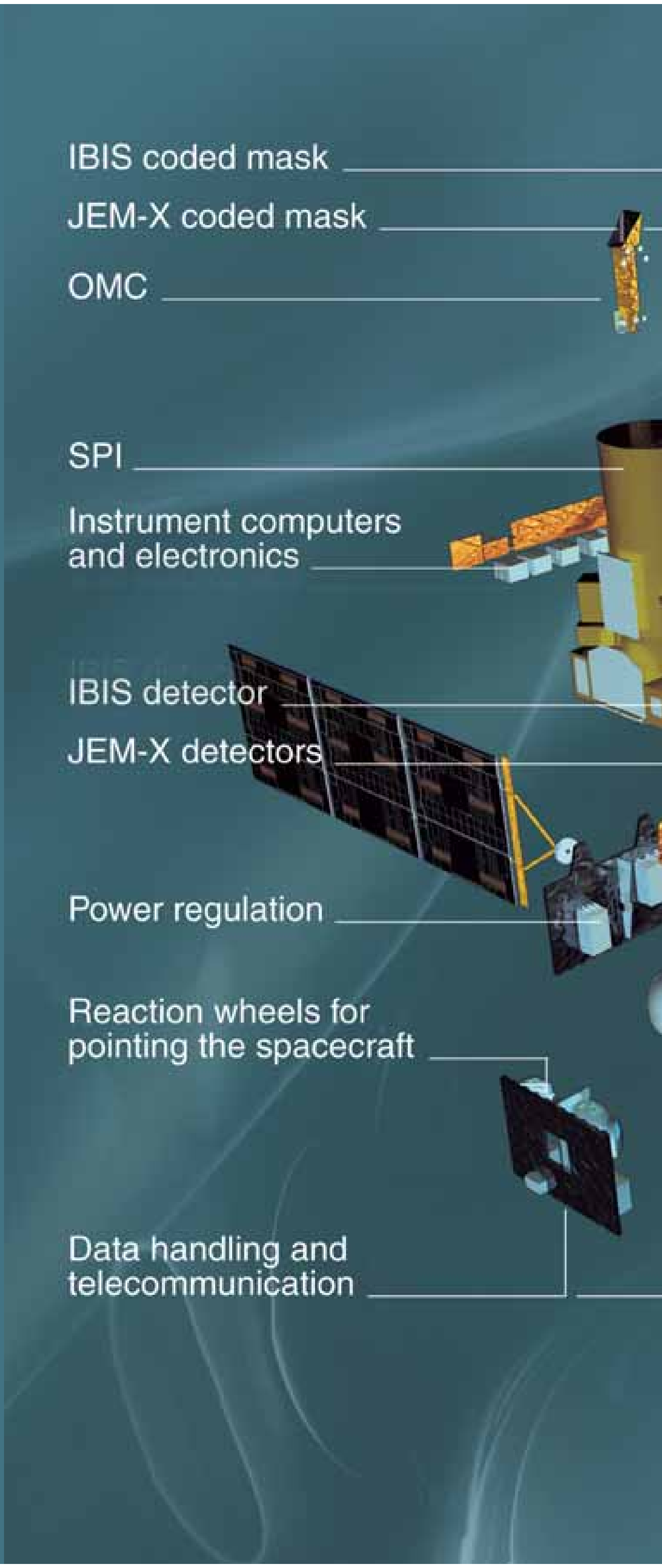
Introduction

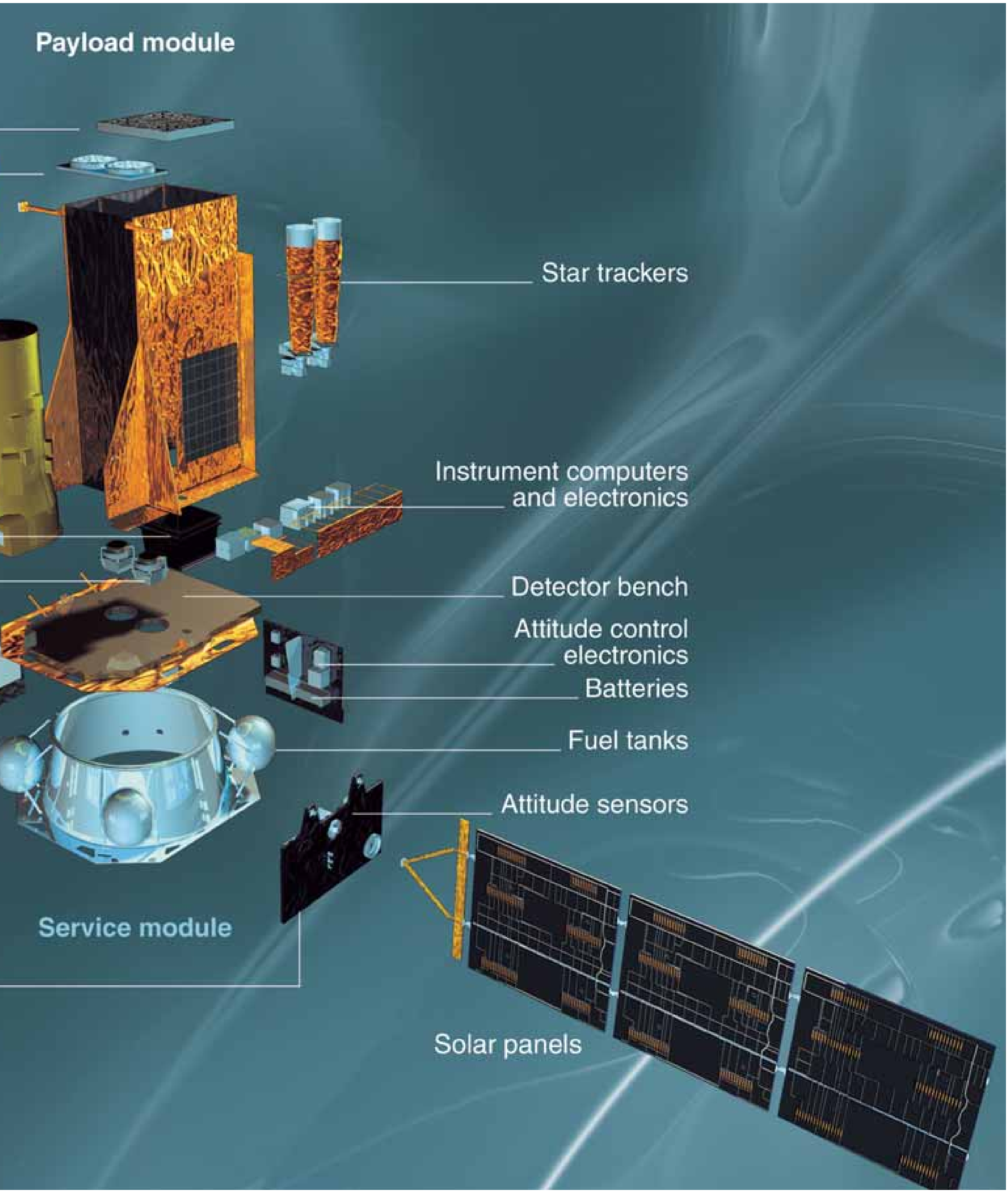
The Integral project began more than 10 years ago, in July 1993, with the aim of providing a full-size high-energy observatory within a medium sized budget. ESA actually used less than the medium sized budget, but it certainly required a great deal of energy to get there. The project had to struggle with a series of challenges: the spacecraft bus was to be shared with the XMM-Newton mission, but to be procured and integrated by a different prime contractor, Alenia. This worked remarkably well. The launcher Proton was to be provided by Russia in return for observing time, but the political, social and economic turmoil during the changeover from the Soviet Union to the Russian Federation meant that it took many long and agonizing years to turn the intention first into commitment and then reality. But finally we got a wonderful launch and Russia is getting wonderful scientific data in return.

The biggest challenge, however, was the payload. Just after the start of the Integral Project, NASA, which was supposed to provide the spectrometer, pulled out due to alternative priorities and the United Kingdom, supposed to provide the imager and optical monitor, pulled out due to lack of funds. Never was Integral closer to cancellation, and so soon after its inception.

However, in a truly European spirit, brave volunteers stood up to take over. A Franco-German team took on the spectrometer, an Italian-French team the imager, and a Spanish team the optical monitor. How brave they really were soon became evident. The development of these observatory-type instruments with little technology heritage proved to be a formidable challenge. The project team had to get more deeply involved and had to provide much more support than foreseen. The launch date had to be postponed three times due to payload problems! Again, finally we got there.

In view of these challenges and looking back over all the busy, exciting and exhausting years of our lives dedicated to Integral, we are even more satisfied and happy to have achieved a perfect launch and a smooth commissioning in orbit, and then to have witnessed a year of flawless spacecraft operations and promising scientific observations.




Payload module
Star trackers
Instrument computers and electronics
Detector bench
Attitude control electronics
Batteries
Fuel tanks
Attitude sensors
Service module
Solar panels

Launch Campaign

The launch campaign lasted less than two months - a rather short time frame for a large, one-of-a-kind satellite like Integral. The campaign began in earnest on 25 August 2002 with the arrival of the two satellite modules at the Baikonur Cosmodrome in Kazakhstan. After reassembly, final electrical verifications, link checks with ESA's European Space Operations Centre (ESOC) in Darmstadt (D), and fuelling, Integral was ready for mating with the Proton launcher. On 12 October, five days before the scheduled launch, the complete launch vehicle, with Integral safely under the upper-stage fairing, was rolled out of the assembly hall at precisely 06:30 local time. By 11:00, the launcher, now clamped in a vertical position, was ready for the final five days of preparation and ground checks.

The launch of Integral from Baikonur on 17 October 2002

October 17 - Launch Day

It was a cold start to the day in Baikonur, with early-morning temperatures of around –7°C, as the ESA and Russian teams made their way to their respective work areas for the final countdown. Six hours before launch, the job of fuelling the first three stages of the Proton launcher with more than 600 tons of propellant began. Three hours later, the process was complete. Despite strong high-altitude winds, in excess of 100 km/h at 11 km altitude, which were close to the limit of acceptable launch conditions, the go-ahead was given to power-up Integral. About 1 hour before lift-off, the relevant authorities confirmed the launch and gave permission to pull back the service tower. Integral, now powered by its own batteries, was switched into launch configuration by ground controllers. Ten minutes before lift-off, the spacecraft and ground segment confirmed their readiness for launch to the launch authorities. At 04:41 UT, right on schedule, the Proton rocket powered off the launch pad and into the sky.

The First Phase of the Flight

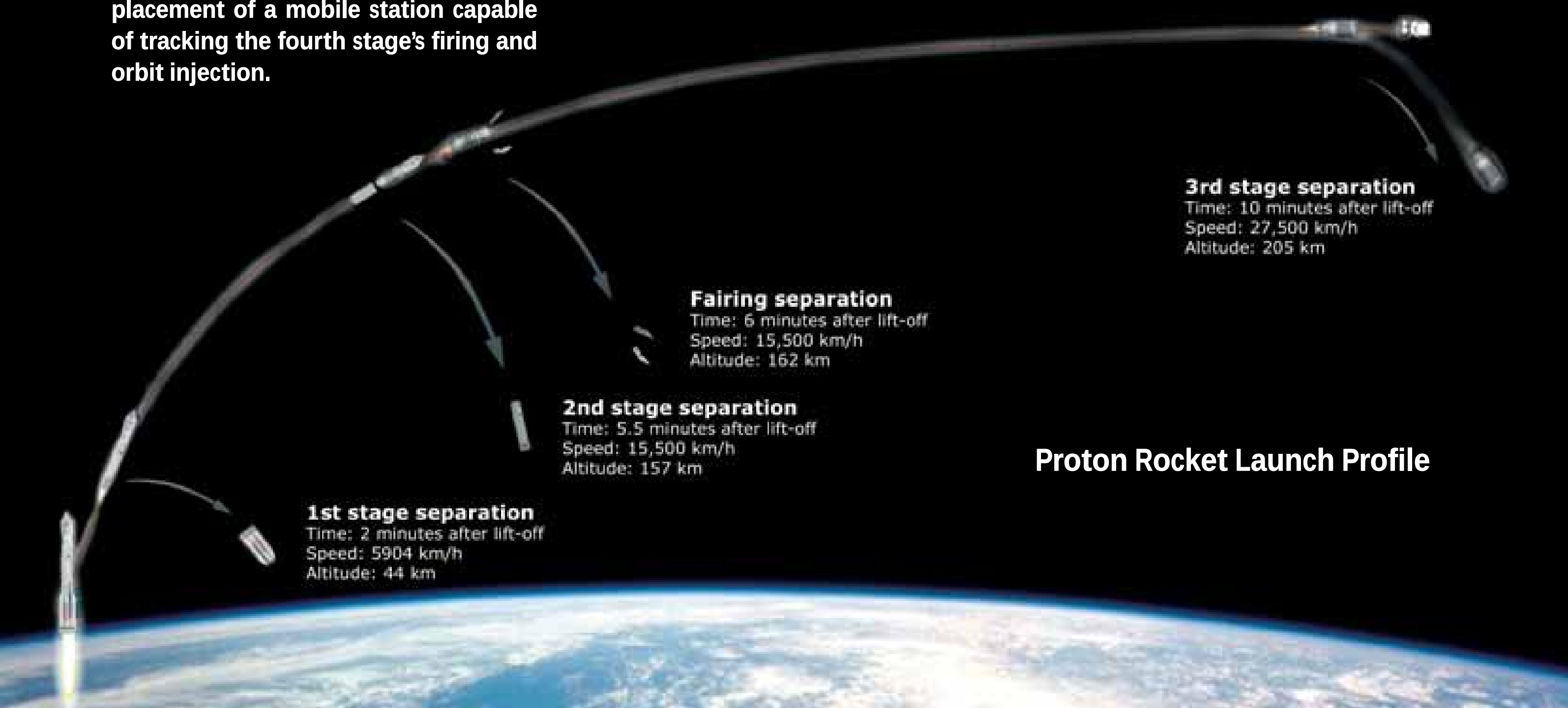
Just ten minutes later and the first three stages of the launcher had boosted the fourth, or upper, stage into a 192 by 690 km parking orbit. This first success was a source of great satisfaction for the teams watching around the world. Subsequent analysis of the Proton flight environment indicates that the flight loads were much lower than predicted. The maximum accelerations, equivalent sine levels and acoustic loads were all well within the qualification levels applied during spacecraft testing.

The fourth stage and Integral were now heading south, over the Southern Pacific, before heading back north, over South America for the fourth-stage burn and satellite separation.

Final Orbit Insertion

The fourth stage of the Proton launcher boosted Integral into a highly eccentric orbit. The Russian company Energia was both the supplier of this stage (Block-DM) and in charge of the tracking and control operations. The firing of the Block-DM was to take place over Argentina and was essential to the success of the mission. Energia did not possess any tracking capabilities in South America, so they approached the Integral Project Team for support in the placement of a mobile station capable of tracking the fourth stage's firing and orbit injection.

Date	Time	Event
25-08-2002		Arrival of Integral at Baikonur
12-10-2002		Integral rollout
16-10-2002	22:41:00	Start propellant loading of Proton rocket
17-10-2002	1:49:00	Integral spacecraft powered up
	3:23:00	Start service tower rollback
	3:36:00	Start of check-out of US
	3:55:00	Completion service tower rollback
	3:56:00	Start of check-out of LV
	4:11:00	Integral declared ready for launch
	4:36:00	LV declared ready to launch
	4:39:00	US is initialised and changed to internal power
	4:39:07	US declared ready for launch
	4:40:58	Lift-off command - launch irreversible
	4:41:00	LIFT OFF
	4:50:50	Separation of orbital modules (US and Integral) - Injection into parking orbit
	5:01:00	End of radio contact
	5:41:37	Radio signal acquired in Argentina
	5:43:22	Start of US Main Engine burn
	5:50:27	End of US Main Engine burn
	5:53:12	End of radio signal over Argentina
	6:01:30	Radio contact with Vilspa
	6:04:22	Radio contact with Redu
	6:10:10	Radio contact with US and Russian ground stations
	6:13:26	Integral separation from US
	6:27:26	Deployment of 1st solar panel
	6:31:26	Deployment of 2nd solar panel
	8:08:26	Swith on of star tracker A
	16:00:00	Switch on and activate IREM
	18:22:00	Start of SPI Activation
	22:32:00	Start of JEM-X 1 activation
18-10-2002	0:30:00	Start of JEM-X 2 activation
	18:35:00	Start of IBIS activation
19-10-2002	6:00:00	Start of OMC activation
20-10-2002	0:00:55	Perigee passage - end of orbit 1
24-10-2002	6:00:00	Start of first orbit manoeuvre (PRM)
31-10-2002	9:54:53	Start of final orbit manoeurve (AAM)
03-11-2002		JEM-X Detection of Cyg X-3
05-11-2002		1st SPI gamma-ray image
14-11-2002		JEM-X Detection of LMC X-3 and LMC X-4
17-11-2002		IBIS, SPI and JEM-X detection of Cyg X-1
25-11-2002		1st GRB imaged by IBIS
18-12-2002		Integral first light
19-12-2002		1st GRB detected by IBAS in IBIS field of view
30-12-2002		End of PV phase
29-01-2003		ISGRI detection of 1st transient source
31-01-2003		GRB, 100 s duration, imaged by IBIS
27-02-2003		1st SPI image and spectrum of GRB030227
20-03-2003		GRB030320 - 5th GRB
16-05-2003		Data distribution to guest observers
15-07-2003		2nd Announcement of Opportunity
11-08-2003		Integral completes 100 orbits
17-10-2003		Integral celebrates 1 year in orbit



Proton Rocket Launch Profile

One of the mobile support stations installed at Mar del Plata in Argentina

After an intensive effort at the technical, logistical and human level (including a visit by ESA's Director General to Argentina) between the Integral Project Team, CONAE (the Space Agency of Argentina) and Energia, the mobile stations were on their way by ship to Buenos Aires. The Argentineans were, from the outset, extremely friendly and helpful, and so the potentially daunting importation and customs formalities were quickly dealt with.

"Being the only Spanish speaking member of the Project Team I volunteered to support the mobile station campaign in Argentina. Of course, I was sad to leave the launch campaign activities in Baikonur, but it was a pleasure to liaise with the Argentinean space authorities."
Eliseo Balaguer

Soon the convoy was speeding along the highway to Mar del Plata with two Russian vans, a team of six Russians, two Argentinean drivers, an interpreter and a CONAE representative. Part way through the journey we had a brief moment of panic when the police stopped the Russian vans - but it was only to ask them to deliver official documentation to the next police station!

Our destination was a fishing research institute conveniently located in the port region of Mar del Plata with a good view of the Integral orbit. The Russian team did an excellent job in installing the stations in a very short time. In fact the job was done so quickly that the next day there was a 'technical first' in the Southern Hemisphere: the cosmonauts aboard the International Space Station switched on a Soyuz transponder as the Station passed over Argentina so that we could validate the mobile stations.

The only disturbing incident before Integral's launch was a torrential storm and subsequent flood that transformed the mobile station site into a swimming pool, forcing us to improvise scaffolding for the station cabling with ladders and other materials.

In Mar del Plata it was almost quarter to two in the morning when Integral was launched. The night was, for the first time in a while, very cold and clear. It was a joy one hour later to see the satellite's rocket engine firing, not only from the telemetry readout on the screens, but also physically in the sky, clearly moving towards its new orbit.

The media coverage in Argentina was impressive with front-page features in local and national papers and a small story on Integral on prime-time TV, which filmed the operations of the mobile station. It was an exciting experience to witness the launch in this way and all the members of the team remember the friendly and warm support from Argentina.

Spacecraft Commissioning

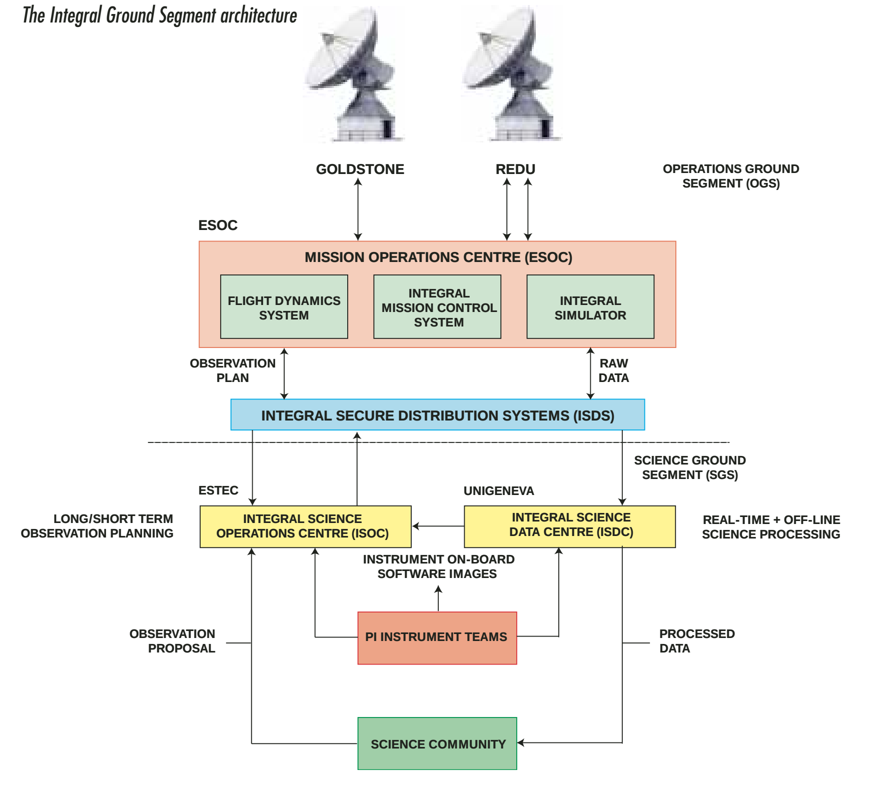
For most launch-team members, the tremendous anxiety that accompanies any launch evaporates at lift-off into scenes of jubilation. But for those who have specific post-launch tasks, both at

the Launch Site and obviously at the Control Centre, the realisation that rocket and spacecraft have left home for good blends with the awareness that the road ahead is long and treacherous and the real excitement is yet to begin. An intense but contained satisfaction therefore permeates the entire Control Centre.

Sitting in the Main Control Room at ESOC, a brief scan around the room would reveal a crowd of familiar faces, concentrating hard, and glued to their monitors; both newcomers at their first launch and seasoned engineers, all experiencing the full spectrum of emotions as events began to unfold. Years of study, diligent effort and intensive training would be finally brought to bear, starting from the moment of 'separation'. From this event on, the success of the Integral mission would literally depend on their timelines, procedures, brains and fingertips.

The operations teams at ESOC had been in contact with the launch site throughout the countdown phase, monitoring the status and health of the

The Integral Ground Segment architecture



onboard systems until just before lift off. The first telemetry contact was established from the Spanish ground station in Villafranca, the announcement flashed through the intercom to all positions. We were still 10 minutes from separation when the ESA ground station at Redu (Belgium) confirmed, 3 minutes after the first contact, that Integral was on track and performing well.

"I lay back on my seat, savouring for a split second the privilege of being part of the extraordinary organisation of teams and technology that makes such a space mission possible. Even after many simulations, even for toughened engineers, the thrill of the real thing is irresistible. So irresistible that the second shift team is also slowly gathering around the workstations; they will rest after separation and after the array deployment, of course; who could sleep anyway?"
Paolo Strada

Exactly 1hour 32minutes and 26seconds after lift-off, as planned, the spacecraft separated from the Proton upper stage and the automatic activation of the onboard systems took place flawlessly.

The familiar separation sequence, rehearsed during so many simulations, was now executing for the last time, for real. Gradually, almost magically, four tons of satellite sprang into life, with communication with the onboard system established, and all of the units essential for attitude control, computer, propulsion

The Main Control Room at ESOC in Darmstadt on launch night

The instrument teams in the Payload Control Room at ESOC, during the activation of the first instruments

valves and heaters, attitude and rate sensors switched on. The spacecraft attitude was 'safe', with initial rates almost at zero, and a few degrees off Sun-pointing, which the controller promptly recovered within a minute. The launch inhibits were all cleared and a quick real-time analysis of the telemetry showed that the power and thermal subsystems were also functioning correctly.

In the meantime, Flight Dynamics had received the orbital element data from Moscow and had begun analysing them to compare the Russian predictions with their own. An exceptionally good orbital injection manoeuvre had placed Integral into the desired orbit with just very small errors.

Anxiety remained high at the Control Centre as the time for solar-array deployment approached. The array release sequence initiates, automatically, ten minutes after separation, but contingency procedures are readied, just in case…

The thermal knives were activated and the two solar panels gradually deployed. There was a mixture of relief and satisfaction as the current from the first array began to increase. Eventually, the array status telemetry changed too, as the panel latched and its telemetry indicated 'deployed'. Four minutes later, the second panel was also out. We had power and began acknowledging cautiously that things seemed to be going exceptionally well.

The background noise in the control rooms increased suddenly as people began shaking hands and patting each other on the shoulder. It is indeed one of the best moments in life when you can shake hands with your colleagues and say: "*We did it!*"

The second-shift team left the scene to get some rest. There was still lots of hard work ahead, including critical attitude-control operations, delicate orbital manoeuvres, convoluted onboard calibrations, but also the feeling at ESOC that Integral was going to be a superb mission.

The next few days were equally successful, as the orbit's perigee height was raised in several burns from the initial 651 km to the final perigee altitude of 9000 km. The parameters of the final orbit turned out to be extremely close to the expected values.

Achieved versus expected orbit parameters

PARAMETER	ACHIEVED ORBIT	EXPECTED ORBIT
Semi-major axis	87 731.5 km	87 678.14 km
Eccentricity	0.824 148	0.813 202
Inclination	52.246°	51.6°
Perigee Height	9049.6 km	9000.0 km
Apogee Height	153 657.2 km	153 600.0 km
Orbital Period	72 hours	72 hours

Performance Verification

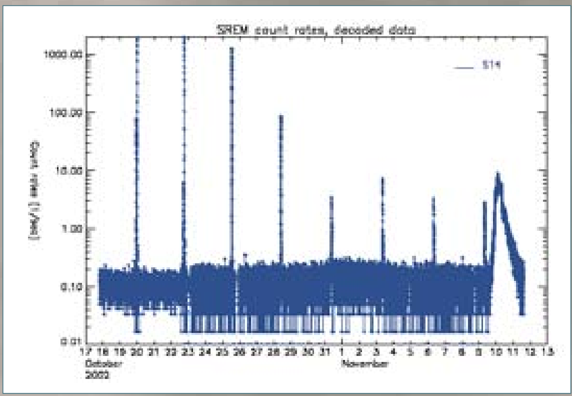
The payload group had sat ready in the Payload Control Room at ESOC eagerly awaiting the launch. After seven years of work that had included many highs and lows, they were at the point where all the verification and careful planning came down to a simple and basic question: Would it work?

After the highly successful chain of events covering launch, stage separation and orbital deployment, as the solar arrays deployed the computer displays showed the electrical current increasing steadily as the panels collected more and more sunlight. At last the power was on, allowing the system team to monitor the hundreds of parameters and confirm the flawless activation of all units. All sub-systems were nominal and the spacecraft was in its right orbit and had the correct attitude. Integral's instruments were still 'sleeping', however, and it would take another three weeks to bring them all to life.

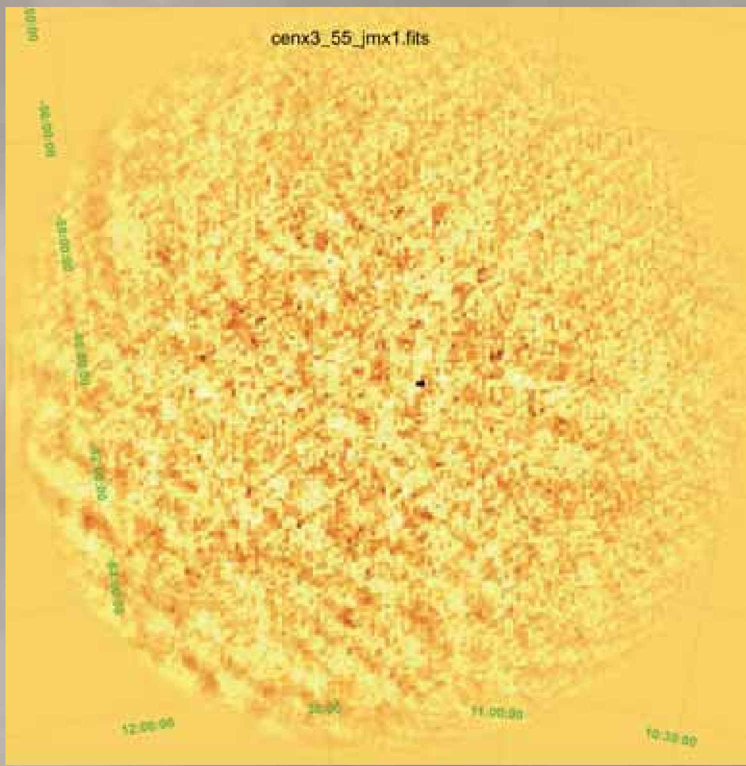
The activation of the instruments had been planned to the last detail. The necessary procedures were in place and had been carefully rehearsed by the Mission Operations team together with the scientists and technicians responsible for each instrument.

First, the instrument electronics were powered up to stabilize the thermal environment on the spacecraft. The first instrument to become operational was the radiation monitor, IREM.

The next instrument to be brought to life was the Optical Telescope. With its

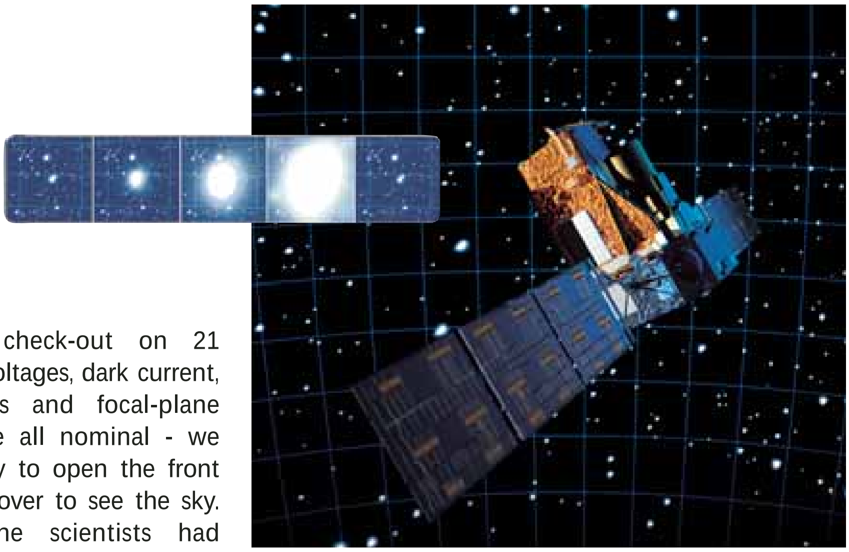


Proton counting rates measured by the IREM instrument from switch-on until mid-November. 'Spikes' occur during each perigee passage as Integral transits the radiation belts. The reduction in the proton flux by almost three orders of magnitude from the initial transfer orbit to the operational orbit is evident. The broad feature around 10 November is associated with solar activity (Courtesy of P. Buehler and the IREM team)



First image of an X-ray star, Cen X-3, obtained with the Joint European Monitor for X-Rays (JEM-X). The star is the small black dot near the centre. Although maybe unimpressive, the image provided the confidence that the instruments are capable of detecting and accurately pinpointing X-ray sources in the sky (Courtesy of the JEM-X team)

'First light' for the Optical Monitoring Camera (OMC) just after the opening of the cover. The brightest star is Gamma Trianguli Australis (Courtesy of the OMC team)



successful check-out on 21 October - voltages, dark current, bias signals and focal-plane temperature all nominal - we needed only to open the front protective cover to see the sky. One of the scientists had displayed on a laptop an image of the part of the sky to which Integral was pointing and which he expected the Optical Telescope to see. The command was given to open the cover, and it took a few minutes for the wax to melt and to release the cover mechanism before the switch position indication displayed on the monitor changed to 'open'. After a few seconds of integration time, the acquired image was downloaded via the spacecraft's telemetry system to the ground station in Redu (B), then sent to the ESOC Control Centre and to the scientists' screens. It was the same portion of sky that our smiling scientist has on his laptop, the same stars, the same positions. One star among them was particularly bright, namely Gamma Trianguli Australis.

On 27 October the next instrument, the X-ray monitor JEM-X, was activated. The high voltages of one of the two units (JEM-X1) were slowly increased in several steps and two days later the same was done for the second detector, JEM-X2, while the satellite was pointing to an empty field. Within a day, an image of the sky was generated by the JEM-X and ISDC (Integral Science Data Centre) teams – testament to the good state of the scientific analysis software. Since there were no bright X-ray sources in this part of the sky, it showed exactly what was expected – an empty image! The JEM-X team had to wait another 2 days until the satellite pointed to a part of the sky that contained a bright X-ray source, before they could be confident that the instrument was working totally as expected. This occurred on 1 November, when Cen X-3, a neutron star with a massive companion, was observed.

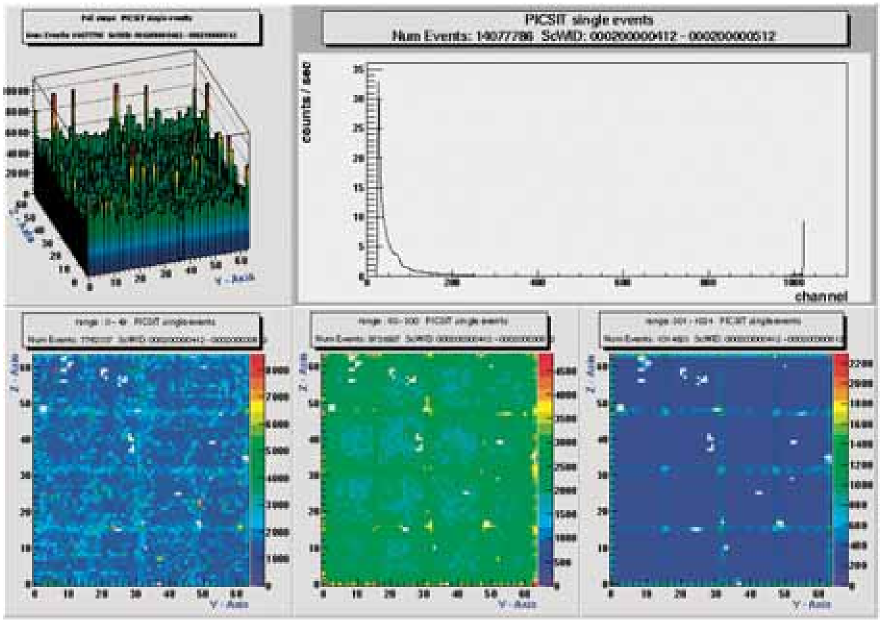
Unfortunately, Cen X-3 was in eclipse for most of the observation and the source was only prominently visible towards the end of the observing period. Nevertheless, the sky-maps for both JEM-X detectors showing the source were available the next day. After JEM-X had switched off twice, triggered by an onboard IREM broadcast message due to the high radiation environment on the descending part of the orbit, it was decided to adjust the critical operation altitude (when the instruments are switched on and off) from 40 000 km to 60 000 km for the descending portion of subsequent revolutions. The altitude at which Integral exits and enters the radiation belts evolves with time, and is therefore continually monitored by the Integral Science Operations Centre (ISOC).

On 7 November it was recognised that a small number of anodes from each of the two JEM-X detectors were suffering degradation. The detector high-voltage settings were lowered by 80 V, which reduced the damage rate significantly. In the following weeks, only three further degraded anodes were found on JEM-X1 and none on JEM-X2. As a precaution, the JEM-X1 high voltage setting was reduced by a further 20 V on 10 December and the instrument has operated flawlessly ever since.

The activation of the Integral spectrometer (SPI) was next and went very smoothly. Shortly after switch-on of the SPI anti-coincidence system (ACS) the first gamma-ray burst (GRB) was observed by the ACS on 27 October at around 08:34 UT, and was named GRB021027. This confirmed the SPI ACS system's ability to trigger on GRBs. The burst was quickly seen in the overall ACS counting rates with a 50 ms time resolution. On 4 November the detector array had cooled to 117 K and the high voltages of the SPI detectors were switched on for the first time in space. Two days later they reached their nominal operating temperature (89 K) and the SPI's performance could be assessed. All the germanium detectors showed excellent performance (with an energy resolution between 2.3 and 2.6 keV (FWHM) at 1.11 MeV, as expected), with the exception of one detector, which had a slightly lower performance (3.2 keV), typical for degradation by pollution. During the first SPI annealing in February 2003 this pollution was cleaned out, and that detector's performance recovered to its pre-launch value.

"*Slowly, but steadily the first images make their appearance on our screens, first the background and then exotic objects. Waves of energy coming from everywhere materialize on our screens. The window to a Universe of explosive ghosts is open.*"
Giuseppe Sarri

The Integral imager (IBIS) is perhaps the most complex instrument onboard the satellite. It consists of two detector layers – the upper layer (ISGRI) is sensitive between 15 and 500 keV and the lower one (PICsIT) between 200 keV and 10 MeV. The PICsIT detectors were activated on 20 October and the first ISGRI detector



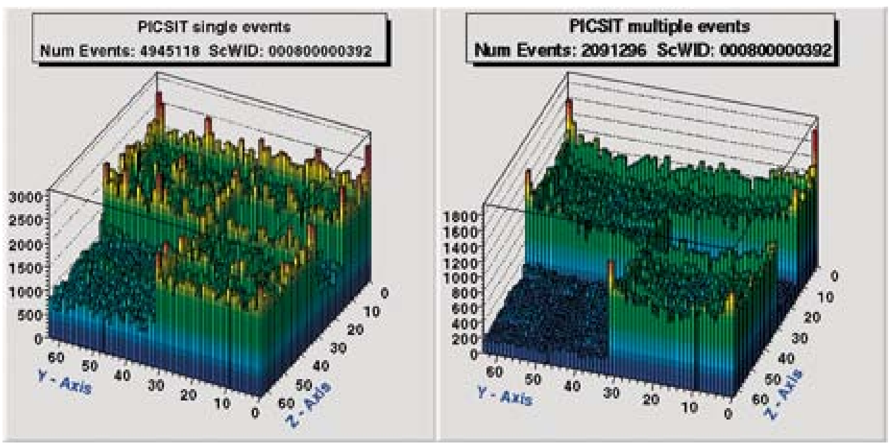
First data collected by the IBIS/PICsIT detector. The diagram at the top left shows the distribution of the events on the detector and at the right the associated detector spectrum for these events. The corresponding shadowgram images at low, medium and high energy are shown below (from left to right, respectively)
(Courtesy of the IBIS team)

four days later. IBIS data acquisition was performed from then on, whenever possible, in order to gain experience of operations, although the high voltages of the veto modules were not enabled until later. Finally, on 7 November, all the veto modules were switched on and the instrument operated in its nominal configuration for the first time in space. The whole team roared their approval when it was clear that IBIS was also working properly, with a performance in line with pre-launch expectations.

However, now that the full complement of Integral instruments was being operated in close to their nominal configurations, it became clear that there was insufficient telemetry capability to transmit all the scientific data being produced. When checking out the instruments, higher telemetry was required by IBIS and SPI in order to optimally tune the onboard event selection filters. During a period with higher telemetry allocation and when PICsIT was operated in photon-by-photon mode, a gamma-ray burst (GRB) occurred within the IBIS field of view. The instrument and the ISDC team reacted quickly and the burst location was communicated to the astronomical community the next day. It is important that accurate GRB positions are quickly communicated in this way as it allows other astronomers to search for the short-lived X-ray, optical and radio afterglows. To the relief of the Integral scientists, the initial burst position was consistent with that derived much later from triangulation using the Interplanetary Network of spacecraft. This result was a milestone for Integral, demonstrating its fine imaging and timing capabilities and the ability to respond quickly and accurately to events occurring in the sky.

The transition from the instrument activation and commissioning phase to the performance and verification phase was gradual, and began on 15 November and lasted until 6 December. During this period the instruments mainly observed the Cygnus region of the sky in 'staring mode'. On 9 December the first dithering observations were successfully executed. The performance and verification phase continued until 30 December. During this time simultaneous observations were made with other high-energy missions such as ESA's XMM-Newton and NASA's Rossi X-ray Timing Explorer (R-XTE), showing that the instrument calibrations performed on the ground were close to what was being observed in space. However, the Integral astronomers had to wait until February 2003 until the Crab Nebula 'standard candle' was observed before the calibration could be confirmed.

All of the Integral observations made in the 17 - 30 December period were made public and quickly placed into the ISDC science archive, allowing many eager astronomers to get their hands on their first Integral data.



PICsIT detector shadowgrams for single (left) and multiple (right) events. They shows how efficiently the VETO system reduces background noise by suppressing events entering the detector from behind. In this case, 3 or the 8 modules had their VETO system switched on
(Courtesy of the IBIS team)

Space Operations

Operations Summary

Both the ground and space operations segments were active from the beginning of the mission. Despite some initial problems, operations have been conducted with high efficiency with, for example, 97.3% of the slewing manoeuvres executed as planned. The only major changes to the ground segment were made to support an on-board change to the Integral software, which allowed 25% more telemetry to be transmitted to ground. With this change Integral could transmit all the necessary science telemetry, so mitigating the earlier problems highlighted once the full complement of instruments were operational.

The performance of the space segment has remained good and the spacecraft has not exhibited any anomalies that could not be handled by the ground teams. As is only to be expected with such a complex mission, changes to the configurations and operational procedures of the various instruments have been implemented to take into account 'in-space experience', including five patches to the onboard software.

The ISDC is routinely providing data and processed products to observers within 6 weeks of their observations – a remarkable feat given the complexity of the Integral data. For more detailed analyses, the ISDC also provides a complete set of analysis software that can be installed on the user's own computer.

Spacecraft Platform

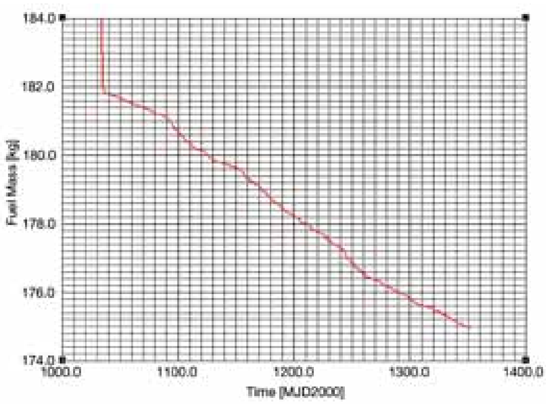
All the Service Module subsystems continue to operate nominally and there have been no major anomalies on any unit. There has been no emergency Sun re-acquisition so far. Full redundancy is still available, with full solar-array power and no degradation identified. There have been periodic calibrations of spacecraft thrusters and sensors to improve operational efficiency.

Eclipses

Two eclipse seasons have been experienced so far. In the winter season eclipses occurred during revolutions 26 to 35, and in the summer season during revolutions 84 to 92. All subsystems performed nominally during these periods. The maximum depth of discharge experienced by the batteries was low, at 21.5% and 27.29%, during the two eclipse seasons.

Fuel Consumption

The fuel consumed so far is 366.9 kg, from an initial 541.9 kg. 359.9 kg was used during the Launch and Early Orbit Phase (LEOP) mainly to raise the perigee height. This left 181.9 kg for operations. The average usage of 0.7 kg/month since then has been for reaction-wheel biasing. There is currently 174.9 kg left for future operations – enough for more than 15 years at the current rate of consumption. The figure below shows the rate of fuel consumption since the final orbit manoeuvre.



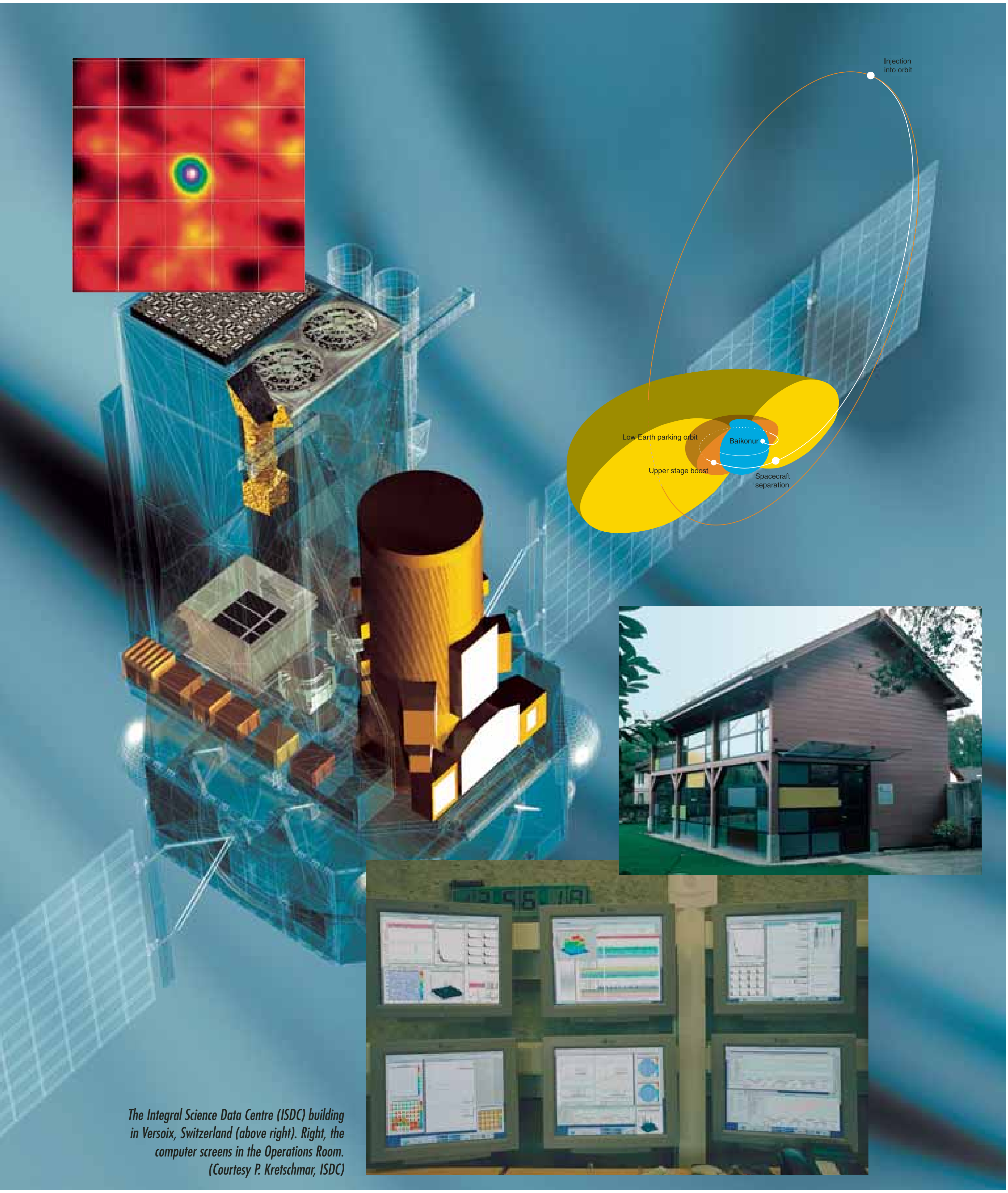
Fuel consumption during the routine mission operations phase (since the final orbit manoeuvre)

Instrument Calibration Activities

The main Integral calibration target for the high-energy instruments is the Crab Nebula. This is a bright high-energy source whose properties change only slowly with time. It has been observed by nearly all the high-energy missions flown and is used for comparing results from one mission to another. Integral has observed the Crab Nebula twice, from 7 to 27 February and from 14 to 17 August 2003. Integral will continue to observe the Crab Nebula every ~6 months in order to monitor the stability of the instruments.

Due to radiation damage to the SPI's germanium detectors, it is necessary to anneal, or bake them out, approximately every 6 months. The first annealing took place between 6 and 13 February 2003 and the second between 18 and 24 July. These have enabled the SPI's energy resolution to be maintained to within 15% of its pre-launch value. The ability to anneal in space is a first for this type of instrument, able to measure the energy of a gamma-ray to 1 part in 500.

The OMC's calibration is maintained by so-called 'flat field' observations. Internal light sources are used to illuminate the CCD detector, allowing the instrument's response to be quantified across the detector plane. It is important that there are no bright stars in the field, so that the intrinsic response can be cleanly measured. The best pointing directions for flat fielding are chosen by the OMC and ISOC teams. Seven such 'flat field' calibrations have been performed by the OMC team.



The Integral Science Data Centre (ISDC) building in Versoix, Switzerland (above right). Right, the computer screens in the Operations Room. (Courtesy P. Kretschmar, ISDC)

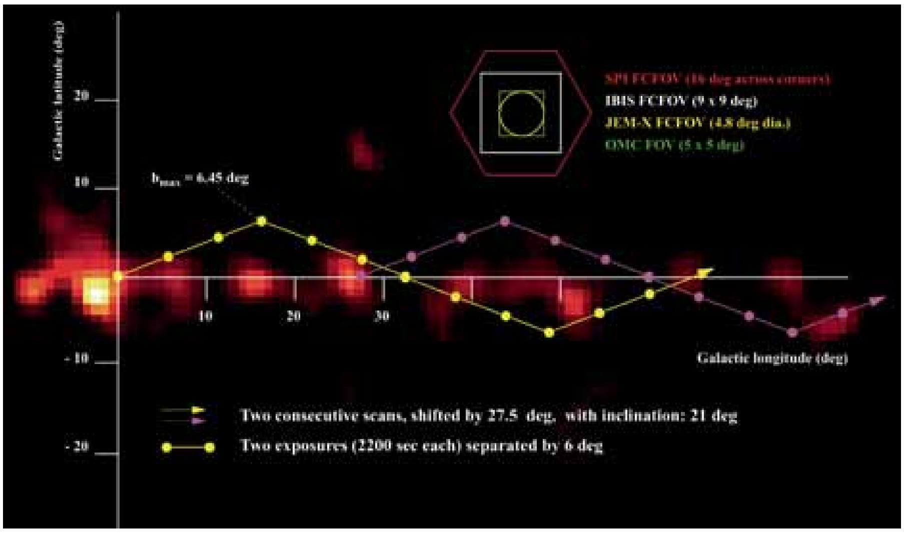
Science Operations

During the first year in orbit, the time available for Integral science operations was divided between the core programme (35%) and general programme (65%).

The general programme time is open to the whole science community, who can submit observing proposals. An independent Time Allocation Committee (TAC) then evaluates the proposals and determines which are to be performed based on scientific merit. The core programme is reserved for the members of the Integral Science Working Team (ISWT) in return for their contributions to the mission. The ISWT is composed of instrument and data-centre principal investigators, mission scientists, the project scientist, and representatives of the US and Russian scientific communities. This ‘core programme’ observing time is used mainly for survey-type activities including regular scans along the Galactic Plane (GPS) and deep exposures of the central radian of the Galaxy (GCDE).

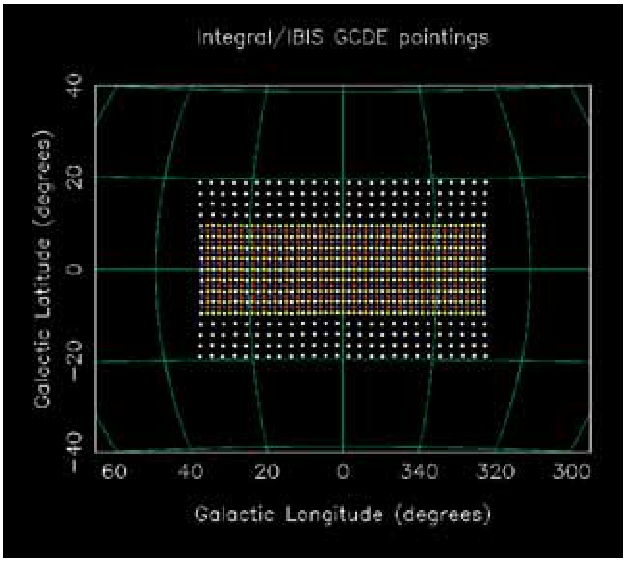
The GPS consists of a sawtooth pattern of observations along the visible parts of the Galactic Plane, in order to search for new and unexpected events (see above figure).

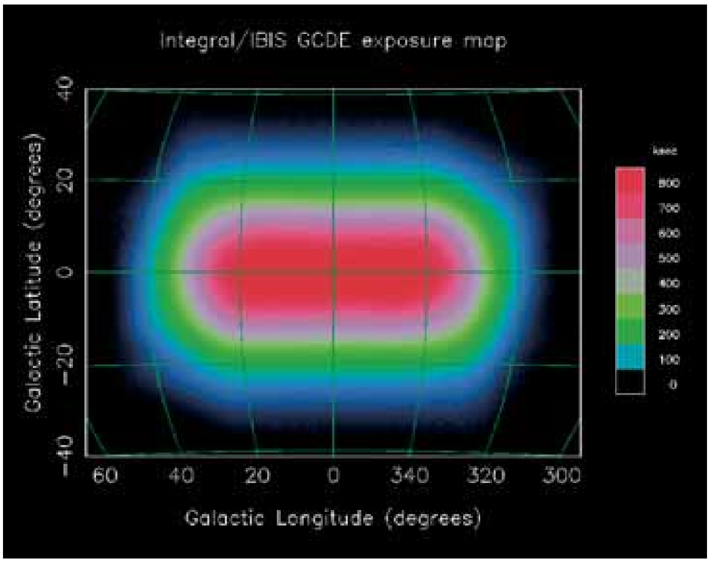
The GCDE observations consist of four different grid patterns covering the Galactic Centre region from –20 deg to +20 deg in galactic latitude and –30 deg to +30 deg in galactic longitude. The four grids, shown in the figure below, are executed twice a year.



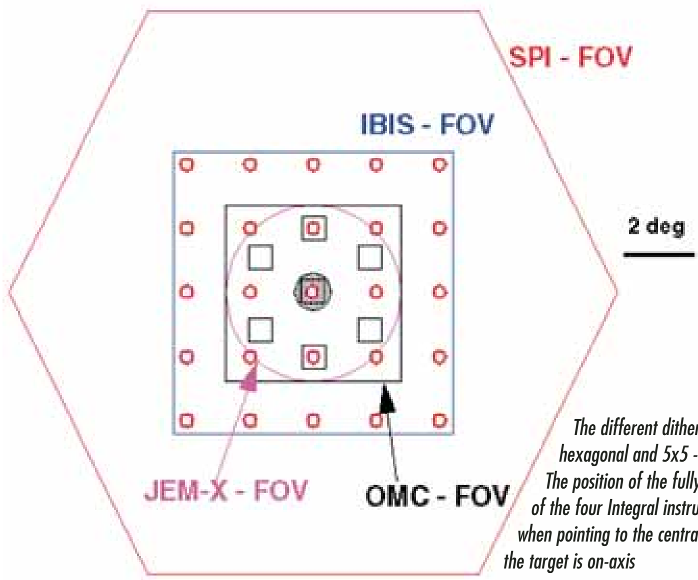
The Galactic Plane Scan strategy. Integral performs scans in a saw-tooth pattern along the Galactic Plane once every 12 days. The saw-tooth patterns of two consecutive scans are shifted by 27.5 degrees. The inset top centre shows the sizes of the fully coded fields of view for the four Integral instruments

The Galactic Centre Deep Exposure is one of the elements of the Integral Core Programme. It consists of four different overlying grids covering the area around the centre of our Galaxy. The left image shows the pointings performed twice within the first year of the mission. The right image shows the exposure map for IBIS after the grid pattern was executed once.
(Courtesy of E. Kuulkers, ISOC)

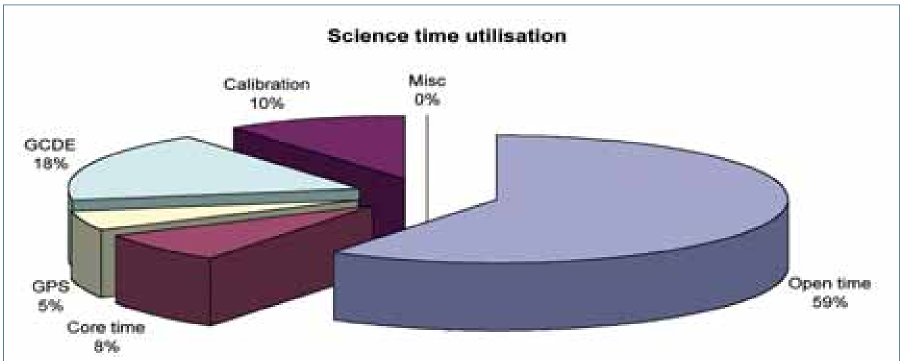




Below is a graphical representation of the statistics of scheduled observations from revolution 26 (30 December 2002) up to revolution 119 (7 October 2003). The total time available to science in this period was around 20.7 million seconds, from which 19.7 million seconds of scheduled scientific observations have taken place. This corresponds to around 95% of the total time available to science. The distribution of the scheduled time among the various types of observations is as follows:



The different dither patterns - staring, hexagonal and 5x5 - used by Integral. The position of the fully coded fields of view of the four Integral instruments is overlaid when pointing to the central position, i.e. when the target is on-axis

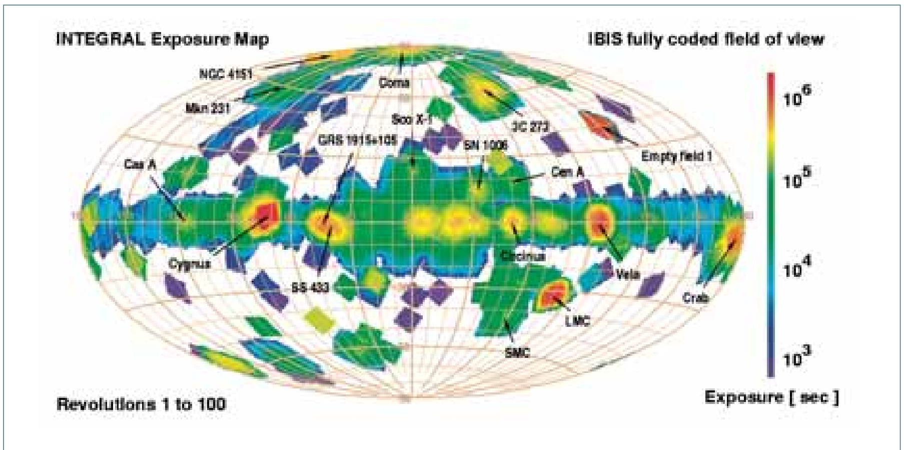


Distribution of the Integral observing time between the different observation categories. 19.7 million seconds of scientific observation time was scheduled in the period from 30 December 2002 to 7 October 2003. 10% of the time was used for calibration purposes, 59% to observe targets from the AO-1 open time programme, and 31% to execute the Core Programme elements (GCDE, GPS and pointed observations)

During this period 67 observations have been made of 54 approved targets (not including GPS and GCDE surveys). In order to obtain maximum science when observing a target there are three possible ways to perform an observation. Integral can constantly point at a target at the centre of the instrument's field of view (so called 'staring'). Alternatively, it is possible to perform a small scan around the target, which is called 'dithering'. There are two dither patterns possible: a 7-point hexagonal pattern or a 25-point rectangular pattern. Dithering improves the sensitivity of the SPI instrument, but decreases that of the X-ray monitor. Observers are allowed to choose the appropriate pointing mode for their observations. The figure top right shows the pattern and the relation to the instrument's field of view.

The sky map shown below indicates which areas of the sky Integral has been observing (up to revolution 100, which ended on 11 August 2003) and the amount of time spent.

The Integral whole-sky exposure map (IBIS fully coded field-of-view) in galactic coordinates for the satellite's first 100 revolutions. The integration time is colour-coded according to the scale on the right
(Courtesy of N. Mowlavi & M. Türler, ISDC)



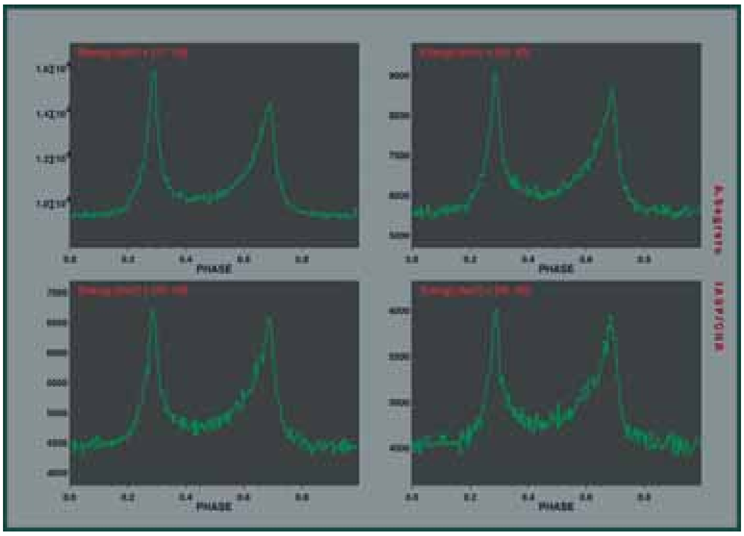
Science Highlights

Many of the early Integral scientific results have been published in 75 papers in a special edition of Astronomy and Astrophysics, issued in November 2003. Given the complexity of the data-analysis techniques required for the coded-mask instruments, the low signal-to-noise ratios inherent in gamma-ray astronomy, and the fact that the Crab Nebula 'standard candle' was not observed until February 2003 due to solar aspect viewing constraints, these results amply demonstrate Integral's potential to contribute significantly to solving many of the outstanding issues in high-energy astronomy. Some highlights are summarised below.

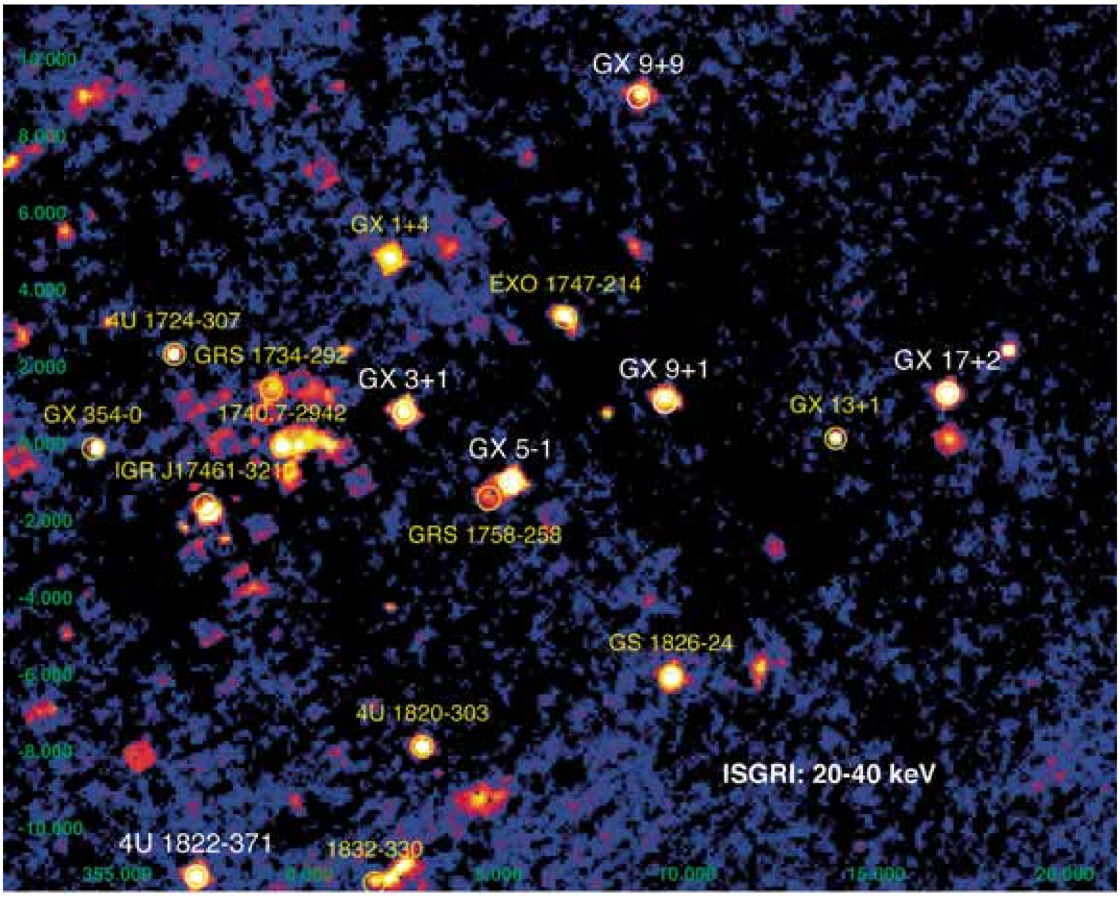
THE CRAB NEBULA

Observations of the Crab Nebula - the standard candle of high-energy astronomy - are essential for the verification of the response models of the high-energy instruments. The Crab Nebula is the remains of a massive star that exploded in 1054 AD and left behind a tiny rapidly spinning neutron star. A neutron star contains the mass of the Sun, but compressed into a tiny ball only 20 km in diameter. The neutron star in the Crab Nebula is spinning 33 times each second and produces flashes as the beamed emission sweeps though the line of sight to the Earth. The neutron star's spin period varies in a predictable way and provides an excellent tool with which to verify the timing capability of Integral. Observations of the Crab Nebula have enabled the Integral astronomers to achieve both goals.

The figure below shows the pulse profile of the Crab pulsar in four different energy ranges measured by IBIS. Two pulses are visible connected by a bridge of emission between them. The absolute phase of the light curve was determined to an accuracy of 40 microseconds. Observations of other gamma-ray sources will benefit from this high absolute timing accuracy of Integral. In the case of the Crab pulsar, the phase shifts between the light curves at different energies



The pulse profile of the Crab Nebula. Each panel shows the profile in a different energy range as measured by IBIS during the February 2003 observations (Courtesy of A. Segreto and the IBIS team)



IBIS/ISGRI image of the area around the centre of our Galaxy in the energy range 20-40 keV. The image covers a region of approximately 24x30 degrees. The many sources visible in the image demonstrate the richness of the Integral data. (Courtesy of A. Paizis and collaborators)

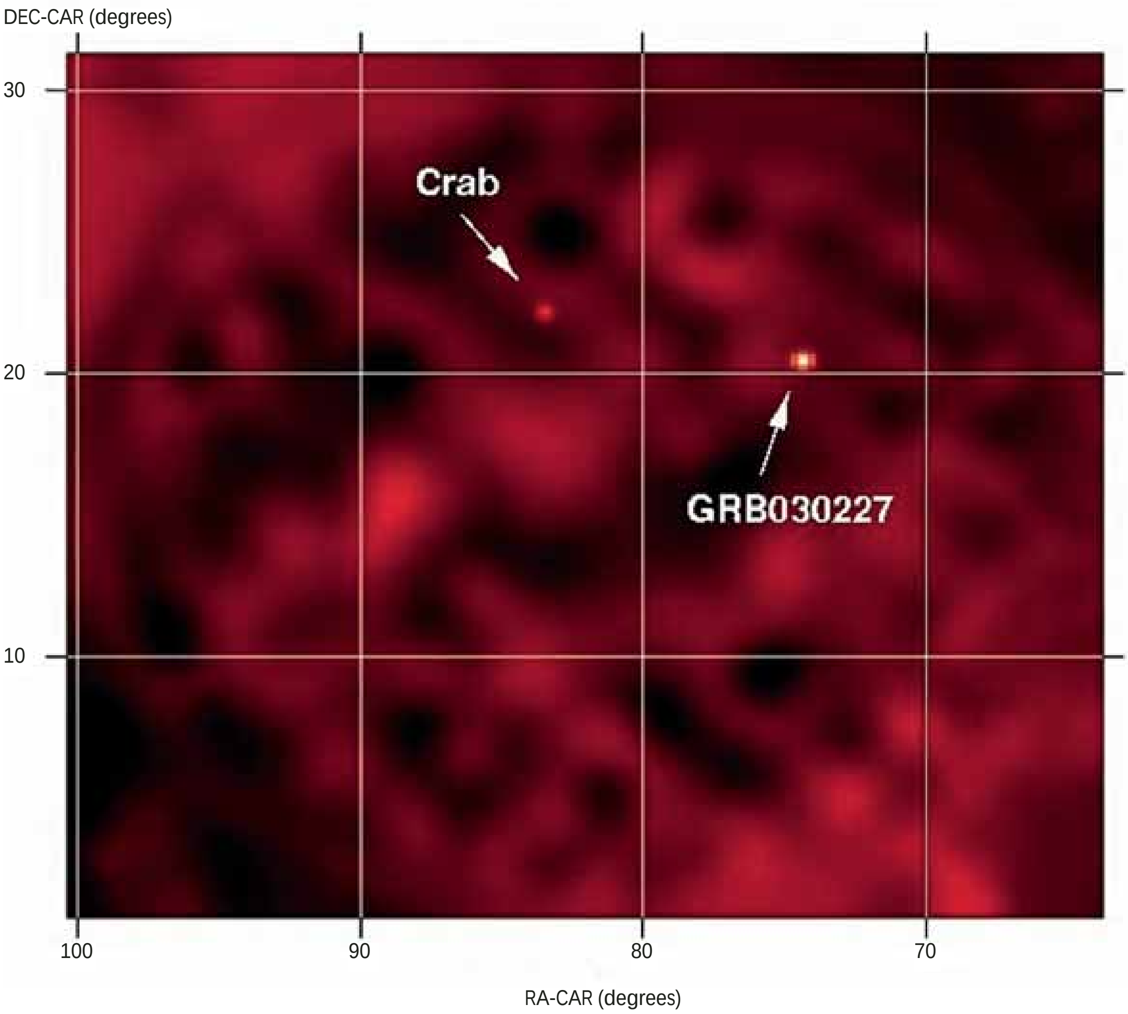
can be used to constrain the three-dimensional structure of the radiation-producing sites in the pulsar magnetosphere.

GALACTIC COMPACT SOURCES

Integral has already detected at least 12 new, strong high-energy galactic sources, all of which have been quickly reported to the astronomical community to allow follow-up observations in different wavebands. As a result, there is a great deal of interest in Integral within the high-energy astronomical community. The first of the 12 sources, IGR J16318-4848, revealed a highly unusual, line-rich, strongly absorbed spectrum in an XMM-Newton follow-up observation. The source was hardly detectable by XMM-Newton below 5 keV due to the strong absorption, while being an intense source in the Integral energy range. This, and the detection of similar sources by Integral, suggests the presence of a previously unknown class of highly absorbed objects. Another of these new sources, IGR J16358-4726, was found to exhibit pulsations with a period of 5850 seconds during a serendipitous Chandra observation. It is unclear whether these pulsations represent the spin or orbital period of the system. During a recent observation of the Galactic Centre region, Integral discovered a new transient source called IGR J17544-2619. Details about the source, including its position, were quickly sent to the astronomical community. The first mission to respond was XMM-Newton, which managed to make a Target of Opportunity observation, even while Integral was still observing the source.

The good coordination between Integral and XMM-Newton, ESA's other high-energy mission, is clearly an asset to the scientific community, enhancing the scientific returns from both missions.

The flexible Integral observing strategy has allowed the mission to respond quickly to interesting and unexpected events. Outbursts from a number of X-ray binaries, such as GRS 1915+105, XTE J16550-564, SGR 1806-20, H 1743-322 and GS 1843+009, have triggered Target of Opportunity observations. The observations of the black-hole candidate GRS 1915+105 were particularly complex being part of a simultaneous multi-wavelength campaign involving Integral, R-XTE, the ESO NTT, the Ryle telescope, NRAO, the VLA, and the VLBA. It is by combining results all the way from radio to the gamma-ray wavelengths that astronomers hope to understand the nature of this microquasar – a stellar-mass black hole accreting from a nearby companion star and producing relativistic jets.



An SPI image in the 20-200 keV energy band showing both the Crab Nebula and the Gamma-Ray Burst (GRB) on 27 February 2003 at 08:42 UT. This was the fourth GRB to occur within Integral's field-of-view. The image was generated from only 18 seconds of data (Courtesy of V. Beckmann (ISDC) for the SPI team)

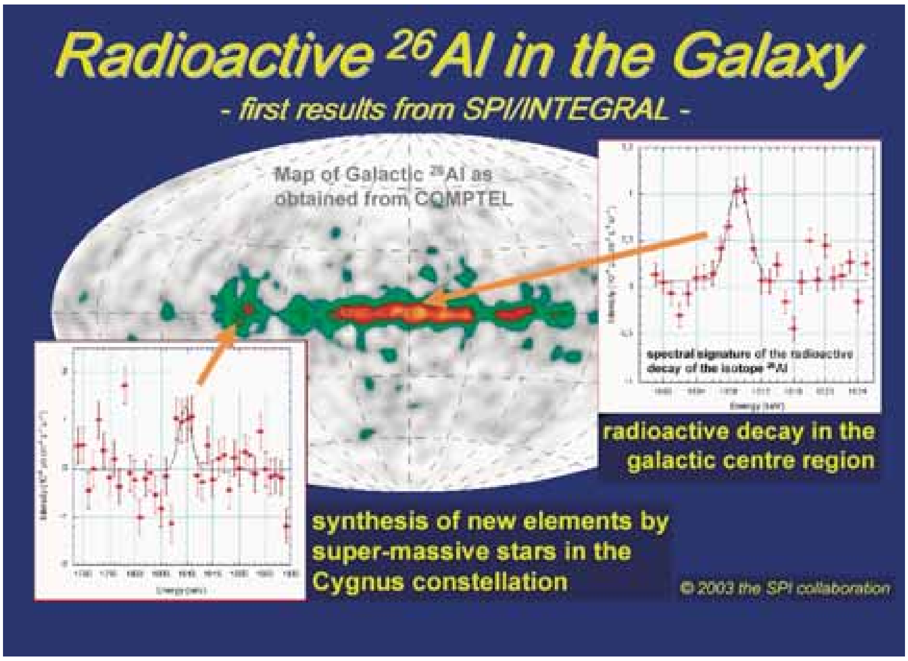
GAMMA-RAY BURSTS

A total of six confirmed GRBs have been observed in the fields of view of the gamma-ray instruments in the first 11 months of Integral operations. This is comparable to the pre-launch estimate of approximately 10 to 20 per year. The automatic Integral burst-detection software, running at the ISDC, provides ~5' source location accuracy within ~15 seconds of a GRB event. These alerts are quickly disseminated to the astronomical community for follow-up observations. Probably the most interesting of the GRBs so far is GRB030227 (see figure). The accurate determination of its position allowed rapid follow-up observations in other wavebands. These revealed a fading 23-magnitude optical counterpart while XMM-Newton, observing only 8 hours after the burst, detected a fading X-ray counterpart and provided a high-quality spectrum. Light curves of around one GRB per day are provided by the SPI ACS. The precise timing provided is combined with results from other missions as part of the Interplanetary Network to provide accurate GRB positions.

DIFFUSE GAMMA-RAY LINE EMISSION

The measurement of the properties of line emission from newly formed elements such as ^{26}Al, ^{44}Ti and ^{60}Fe is one of the key goals of Integral. The high-resolution spectral studies allowed by Integral reveal information about sources, through Doppler broadening, and their location, through shifts from galactic rotation. These emission lines are faint and are distributed over large regions of our galaxy, so that long exposures are required to map and study their properties. Early results suggest that Integral is very well suited to this task.

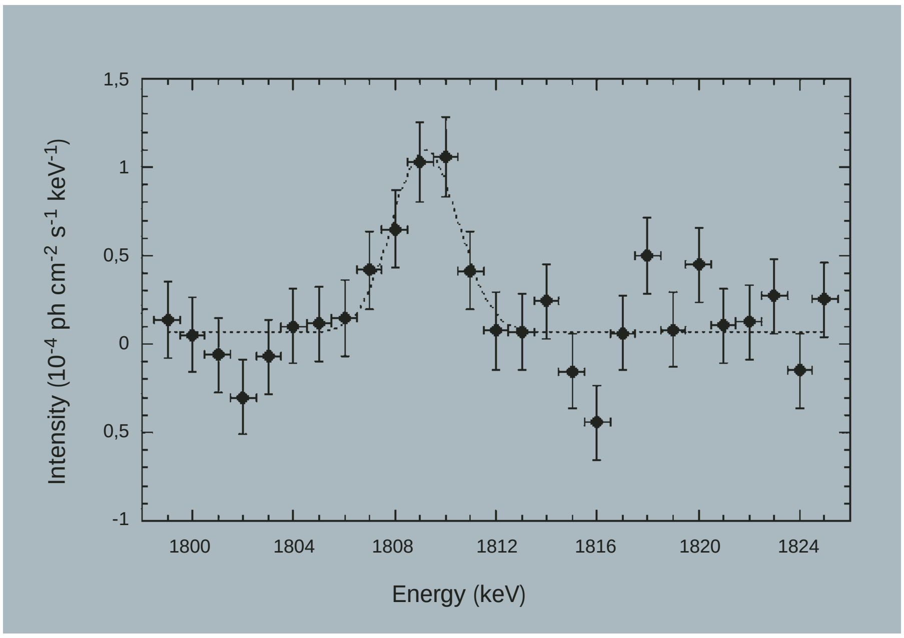
The detection of specific lines shows the SPI instrument's ability to detect gamma-ray lines, even with modest exposures. Already, from just six months of data, the spectral-line resolution is comparable to, or even surpasses, the CGRO results after its nine-year mission. This opens up exciting possibilities for more detailed studies of this line as the Integral mission progresses.



Map of the Galaxy obtained with CGRO-Comptel (1991-2000) in the light of the ^{26}Al line. The insets show the clear detection of this line from the centre of our Galaxy and from the Cygnus area with Integral's SPI instrument after the first months of operation, demonstrating its ability to detect gamma-ray lines even with modest exposures
(Courtesy of the SPI team)

The first six months of observations already hint at the presence of the 1172 and 1332 keV lines from ^{60}Fe in the direction of the Galactic Centre. Since ^{60}Fe and ^{26}Al are probably produced in different ways, the ^{60}Fe/^{26}Al intensity ratio provides important information on the contributions of the different sources to the production of ^{26}Al. The Reuven Ramaty High-Energy Solar Spectroscopy Imager (RHESSI) has recently measured an ^{60}Fe/^{26}Al intensity ratio of about 15%, consistent with the value expected if exploding massive stars contribute most of the ^{26}Al. The ^{60}Fe lines were only detected at moderate confidence by RHESSI, and so Integral will be crucial in providing the first solid detection of ^{60}Fe. Searches for ^{44}Ti line emission (at 68, 78, and 1157 keV) are continuing. ^{44}Ti has a half-life of only 60 years, and so its detection would be a sign of an extremely recent exploded star, or supernova, perhaps hidden by dust that blocks all but the most penetrating photons.

Another high-priority Integral target is the detailed mapping and spectroscopy of the 511 keV electron-positron annihilation feature seen from the central galactic region. An initial analysis of SPI results indicates that the 511 keV line has a width of 2.95 keV, at the upper range of previous measurements. The origin of the positrons (anti-electrons) is uncertain and neutron stars, black holes, supernovae, novae, Gamma-Ray Bursts (GRB), different types of stars, and cosmic-ray interactions with the interstellar medium have all been proposed. Detailed mapping of the emission will provide constraints on the origin of the positrons. Early results from SPI reveal a spherical galactic bulge that may be slightly offset from the Galactic Centre. As yet, there is no evidence for the disk component seen by the OSSE instrument on the Compton Gamma-ray Observatory. However, with the amount of data available so far, the upper-limit is still consistent with the intensity measured by OSSE. As more observations of the Galactic Centre region are performed, it is expected that Integral will produce maps with unprecedented spatial and spectral resolutions and sensitivity.



SPI spectra of the 1809 keV line emission from the Cygnus and Galactic Centre regions, produced by the decay of the radioactive isotope ^{26}Al (with a half-life of approximately one million years). Massive stars are a probable site of formation of ^{26}Al, and this makes it an ideal historical tracer for nucleosynthesis. The observed line intensity is consistent with previous measurements, but is narrower (with a 3.1 keV width) than the 5.4 keV width reported recently by the GRIS experiment

Second Announcement of Opportunity and Future Plans

The second Integral Announcement of Opportunity was open between 15 July and 5 September 2003 for proposals for observations to be performed during the second year of the nominal mission. The total number of proposals received was 142, requesting a total observing time of 144 million seconds. Given that roughly 18 million seconds are available for the open-time programme during the second year of the mission, this is an over-subscription by a factor of eight. The extremely high degree of over-subscription shows the continued high degree of interest in Integral from the scientific community. Combined with the encouraging early results emerging from Integral data analysis, and the fact that the satellite is in an excellent state (there is still fuel for more than 15 years of operation), there is great hope that the Integral mission will be both long and highly successful. With this in mind, plans are already underway to request an extension of the mission until the end of 2008. Should such an extension be approved, it is planned to move the ISOC from ESTEC to ESA's VILSPA facility in Spain, to benefit from co-location with the XMM-Newton Science Operations Centre.

The excellent mission status and the scientific results available so far would not have been possible without the combined efforts of all parties involved – all of whom did an outstanding job. This includes the industrial consortium, the Proton launcher team, the Project Team, the Mission Operations Centre (MOC) team and all the scientists from the instrument teams, ISDC and ISOC. We thank them all and look forward to even more exciting results from Integral in the future.

The Integral Team assembled at ESOC, in Darmstadt (D), on the day before the launch, with a quarter-scale model of the spacecraft

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Contact: ESA Publications Division
c/o ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands
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